IO: EVIDENCE FOR MAJOR VARIATIONS IN REGOLITH PROPERTIES FROM GALILEO IMAGES. D. P. Simonelli and J. Veverka, *Center for Radiophysics and Space Research, Cornell University, Ithaca NY 14853, simonelli@cuspif.tn.cornell.edu*, A. S. McEwen, *Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721*, and the Galileo Imaging Team.

The colors and albedo contrasts of many regions on Io change significantly between Galileo SSI images taken at different times with different lighting-and-viewing geometries. The changes are most widespread and extreme in an area that extends from Pele through the western half of Colchis Regio (latitudes $\pm 60^\circ$, longitudes 190–255°W). Although some of these changes, in the immediate vicinity of Pele, may be associated with this volcano's active plume, the more widespread changes are caused by region-to-region variations in the Ionian surface's regolith properties, properties which determine how the surface scatters light under different geometries.

Observations

Green-filter (0.56 μm) images of the Pele/Colchis region obtained during the first two Galileo orbits (orbit G1, 6/96, solar phase angle α = 55°; orbit G2, 9/96, α = 4°) have been corrected for limb-darkening and phase effects using Voyager and Earth-based information on Io's global-average photometric behavior (McEwen et al. 1988, Simonelli and Veverka 1986). The resulting corrected images have been map-projected and ratioed.

Striking changes in the green-filter albedo patterns are seen in two isolated regions: (1) The single brightest feature on the G2/G1 ratio map is the ring of plume deposits around Pele: this ring is $\approx$ 35% darker than its surroundings on G1, but shows a much more muted contrast relative to its surroundings on G2. (2) The single darkest feature on the G2/G1 ratio map, an 80-km-diameter caldera just east of Pele (12°S, 244°W), experiences a complete contrast reversal: it is a few tens of percent brighter than its surroundings on G1 and several tens of percent darker than its surroundings on G2.

The remainder of the Pele/Colchis area shows smaller, but still major, green-filter contrast changes, and to first order this large latitude/longitude swath can be divided into two units: (1) A unit that is bright on the G2/G1 ratio map. This includes most of Io's bright equatorial band plus a set of flow-like features surrounding the dark eruptive center at 50°S, 218°W. Between G1 and G2, these materials typically brighten by $\approx$25% relative to the dark unit desribed below. (2) A unit that is dark on the G2/G1 ratio map; this unit includes much of the material at higher latitudes. Typically, this material is $\approx$15% darker than the equatorial band on G1 and drops to $\approx$40% darker than the equatorial band on G2. However, a subset of this unit, adjacent to the plumes Pele and Marduk, actually undergoes a contrast reversal, switching from brighter than the equatorial band on G1 to darker than it on G2.

Interpretation

Major changes in Io's albedo patterns can indicate actual time-dependent changes in the satellite's surface or near-surface environment, such as new lava flows or pyroclastic deposits, the appearance/disappearance of "airborne" particulates (e.g., plumes turning on and off), and the temperature-dependent deposition/sublimation of frost layers. However, such contrast changes can also result from variations in lighting/viewing geometry, in which case they are indicative of surface materials with unusual photometric behaviors or parallax effects, changing path lengths, etc., when viewing airborne plume material. We believe that most, and possibly all, of the green-filter albedo changes seen in Pele/Colchis between G1 and G2 are due to variations in lighting-and-viewing geometry rather than actual time-dependent changes:

(1) *The Pele plume deposits:* Examination of one additional green G1 image (α = 25°) indicates that the changes seen by SSI at Pele correlate with emission/phase viewing geometry, not orbit. In other words, regardless of whether an image was taken on G1 or G2, the plume deposits always exhibit lower green-filter contrast relative to their surroundings when viewed near the limb or at lower phase angles. Since HST observations between G1 and G2, and SSI observations from the fourth Galileo orbit (E4, 12/96), confirm that Pele currently has an active plume (McEwen et al. 1997), one possible explanation for the contrast changes is geometry-dependent variations in how the surface is obscured by airborne plume material. Looking at the ring of Pele deposits from directly overhead would give an increased path length through the vertically-falling material, thus providing greater albedo contrast relative to the plume-free surroundings. A problem with this scenario, however, is that the current Pele plume is difficult to detect at green wavelengths (to date HST has seen it only in the UV, and SSI only in the violet). If it is, in fact, impossible to detect the airborne plume material in the green even with a large path length, then the contrast changes observed at Pele would instead have to be attributed to unusual photometric behavior by the plume's surface deposits. (See McEwen 1988 and Spencer et al. 1997 for discussions of changes that have been seen at Pele by Voyager and HST.)

(2) *The caldera east of Pele:* It is tempting to conclude that a new dark lava flow was emplaced here between G1 and G2. However, an image taken during the third Galileo orbit (orbit C3, 11/96) in SSI's broadband clear filter shows little if any contrast between this caldera and its surroundings—and it seems unlikely that unexpectedly rapid phase transformations, a coating of some even newer material, etc., could have brightened up a new dark lava flow this much in the short time between G2 and C3. Unusual photometric behavior provides a more viable explanation for the changes seen at this caldera, for two reasons: (i) The observed contrast changes again correlate with lighting/viewing geometry. (The C3 clear image, at α = 47°, has a phase angle close to that of the caldera's G1 green observation; and spectral information from the latter orbit indicates that if a clear image had been taken on G1 it would show little or no contrast between this caldera and its surroundings, exactly what was seen on C3.) (ii) We have detected a similar green-filter contrast reversal at one other

caldera (Gibil Patera), and in this other case the reversal must be due to photometric effects rather than time variability because the images were taken over a short time period and an extremely wide range in phase angle. (Gibil was imaged at different times during orbit G1 at α = 25°–122°.)

(3) *Remainder of the Pele/Colchis region (the basic bright/dark units on the ratio map):* The green-filter contrast changes that define these units cover such an extensive area that they cannot be attributed to new volcanic deposits, the onset/cessation of plume activity, or plume-related parallax effects. Furthermore, while most of the G1/G2 contrast changes seen in the green also occur in SSI's red and 756-nm filters, there is little or no contrast change—little or no hint of these two units!—in the corresponding images taken through SSI's violet filter (λ = 0.42 μm). No known time-dependent process can produce the required color changes, i.e., all volcanic processes and frost-deposition processes that can produce major green-filter contrast changes are expected to significantly affect violet albedo patterns as well. Only variations in the photometric behavior of the surface from unit-to-unit can produce the observed effects, as we now demonstrate.

Discussion

The bright unit on the G2/G1 green ratio map is unusually bright at 4° phase relative to 55° phase; therefore, this is a material that is strongly backscattering in the green filter. Conversely, the ratio map's dark unit, unusually dark at 4° relative to 55°, signifies a material with a less-backscattering green behavior. What unit-to-unit variations in Io's surface properties might be responsible for these different backscattering behaviors? The fact that the visibility of the albedo changes varies so strongly with wavelength suggests that local variations in the macroscopic roughness of the Ionian surface are not the main cause of the effect. The fact that the lowest phase angle in use, 4°, only reaches into the "shoulder" of the opposition surge also makes it questionable whether surge-related effects like variations in regolith porosity are a major contributing factor. (SSI didn't explore deep into Io's opposition surge until E4, when α = 0.5° images of the Colchis/Prometheus/Emakong region were successfully stored on Galileo's tape recorder.) In the end, the only explanation that fits the G1/G2 Pele/Colchis data is that we are seeing major region-to-region variations in the intrinsic backscattering nature of regolith particles.

The photometric parameter that describes the forward-scattering-vs-backscattering nature of regolith particles is the Henyey-Greenstein asymmetry factor g; g for global-average Io at green wavelengths is $\approx$ -0.3 (McEwen et al. 1988, Simonelli and Veverka 1986). We estimate that in order to produce the observed G1/G2 contrast changes, the ratio map's bright and dark units must have green-filter g's that differ by 0.10–0.15. Such a difference is emminently plausible, and may be associated with differences in the size and/or transparency of regolith particles. In particular, the ratio map's bright, more-strongly backscattering unit may have larger, more opaque regolith particles than the ratio map's dark unit. These differences can provide important clues to the range of geologic processes operating on Io, and the relationship between the satellite's young, volcanically emplaced surface and its unusual photometric behavior. For example, the regions adjacent to Pele and Marduk which belong to the less-backscattering unit, and which undergo phase-induced contrast reversals, might represent fresh deposits of small particles near active SO_2 vents.

Voyager did detect photometric color/ contrast changes on Io similar to those seen by SSI (cf., wide-angle Voyager 1 images of a 700-km-long flow at Aten Patera, α = 10–40°), but the ability to detect such changes in 1979 was limited because most moderate-resolution Voyager images of Io were taken at $\alpha \leq 20°$ (when entering the Jovian system) and $\alpha > 100°$ (when leaving the Jovian system). In contrast, the SSI images of Io on G1, G2, and C3 were spread more continuously across a wide range of different phase angles, and this trend will continue on future Galileo orbits. As the SSI Io data set grows, we are likely to detect other photometrically produced changes in the satellite's color and albedo patterns, and of course also hope to see real orbit-to-orbit surface changes caused by volcanic activity. These additional Galileo data will allow us to better constrain, and interpret, the unusual photometric behavior of Io's surface, and gain more confidence in our ability to separate real, time-dependent surface changes from photometric effects.

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